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Precision measurements of the top quark mass and width with the DØ detector

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Since the discovery of the top quark in 1995 at the Fermilab Tevatron Collider, top quark properties have been measured with ever higher precision. In this article, recent measurements of the top quark mass and width using up to 3.6 fb^{-1} of DØ data are summarized. Different techniques and final states have been examined to measure the top quark mass and they agree well within uncertainties. In addition to the direct measurements, a measurement of the top quark mass from its production cross section and a measurement of the top-antitop quark mass difference are presented.

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1. Introduction

With a mass of 173.3 $\pm$ 1.1 GeV [1], the top quark is the heaviest of all known fundamental particles. Due to the high mass, its Yukawa coupling is close to unity suggesting that it may play a special role in electroweak symmetry breaking [2]. Precise measurements of the masses of the W boson and the top quark, constrain the mass of the as-yet unobserved Higgs boson and restrict certain extensions of the Standard Model [3]. At the Tevatron collider, with a center-of-mass energy of 1.96 TeV, 85% of the top quark pairs are produced in quark-antiquark annihilation and 15% originate from gluon-gluon fusion. Top quarks are predicted to decay almost exclusively to a W boson and a bottom quark. According to the type of W boson decays, top events are classified into all-jets, lepton+jets and dilepton events. The lepton+jets channel is characterized by four jets, one isolated, energetic charged lepton and missing transverse energy. With 30%, the branching fraction of the lepton+jets channel is about seven times larger than the one of the dilepton channel whereas the signal to background ratio is about three times smaller. The main background in this final state emerges from electroweak production of W bosons in association with jets. Instrumental background arises from events in which a jet is misidentified as an electron and events with heavy hadrons that decay into leptons, which pass the isolation requirements. The topology of the dilepton channel is described by two jets, two isolated, energetic charged leptons and significant missing transverse energy from the undetected neutrinos. The main background are $Z+$jets and diboson events ($WW/WZ/ZZ+$jets) as well as instrumental background as characterized above. At the DØ experiment, different techniques are used to measure the top quark mass. As sources of new physics beyond the Standard Model could appear differently in different final states, it is important to measure the top quark mass using all final states. The different mass measurements are summarized in the following sections together with the first measurement of the top-antitop quark mass difference and the first precise determination of the top quark width.

2. Top quark mass measurement using the Neutrino Weighting method

In the Neutrino Weighting approach [4], the neutrino momenta are calculated assuming a certain top quark mass as well as different neutrino pseudorapidities. A weight is assigned to each event according to the agreement of calculated neutrino momenta and measured missing transverse momentum. Based on the mean and the RMS of these weights, signal and background templates are built and the top quark mass is extracted from a likelihood fit. The analyzed data set corresponds to an integrated luminosity of up to 1.0 fb^{-1} of dilepton top pair candidate events yielding

$$m_{\text{top}} = 176.2 \pm 4.8(\text{stat}) \pm 2.1(\text{syst})\ \text{GeV}.$$

The main systematic uncertainties on this measurement come from the determination of the energy scale of the jets, the modeling of the simulated signal events and the fragmentation of the jets from b quarks.

3. Top quark mass measurement using the Matrix Element method

The Matrix Element method yields the most precise approach measuring the top quark mass. For each final state $y = (p_1, \ldots, p_6)$ of 6 partons with four-momenta $p_i, i = 1, \ldots, 6$, the probability to originate from the signal process assuming a certain top quark mass $m_{\rm top}$ is given by

$$P_{\rm sgn}(x;m_{\rm top}) = \frac{1}{\sigma_{\rm obs}(m_{\rm top})} \int {\rm d}\varepsilon_1\ {\rm d}\varepsilon_2\ f_{\rm PDF}(\varepsilon_1)\ f_{\rm PDF}(\varepsilon_2)\ \frac{(2\pi)^4\,|M(y)|^2}{\varepsilon_1 \varepsilon_2 s}\ {\rm d}\Phi_6\ \ W(x,y)\ , \quad (3.1)$$

where ε_1, ε_2 denote the energy fraction of the incoming quarks from the protons and antiprotons, $f_{\rm PDF}$ the parton distribution function, s, the center-of-mass energy squared, $M(y)$, the leading-order matrix element [5] and $d\Phi_6$, an element of the 6-body phase space. The finite detector resolution is taken into account using a transfer function $W(x,y)$ that describes the probability of a partonic final state y to be measured as $x = (\tilde{p}_1,\ldots,\tilde{p}_n)$. The signal probability is normalized with the observable cross section $\sigma_{\rm obs}$. In a similar way, for each event the probability to arise from background is calculated. Taking the huge amount of computing time into account, only the leading source of background is considered, i.e. $Z+$jets probabilities in the dilepton case, $W+$jets probabilities for lepton+jets. Both probabilities are combined into an event probability and the top quark mass is extracted from a likelihood fit. To calibrate the method and correct for any bias, Monte Carlo simulated events are used to perform ensemble tests.

In the dilepton channel [6], the analyzed data set corresponds to an integrated luminosity of up to 3.6 fb^{-1} of electron+muon events. The top quark mass is measured to be

$$m_{\rm top} = 174.8 \pm 3.3({\rm stat}) \pm 2.6({\rm syst})\ {\rm GeV}.$$

The dominant sources of systematic uncertainties are jet uncertainties, such as jet energy scale and resolution. With a statistical uncertainty of 3.3 GeV, this measurement has the smallest uncertainty of all top mass measurements performed in the dilepton channel at the DØ experiment.

As the largest systematic uncertainty on the top quark mass arises from the jet energy scale and as one of the W boson decays hadronically in the lepton+jets channel, the well known W boson mass can be used to constrain the jet energies. An additional scale factor is introduced in Eq. (3.1) and both the top quark mass and the jet energy scale are measured simultaneously.

In the lepton+jets channel [7], an integrated luminosity of 3.6 fb^{-1} of data is used and the top quark mass is measured to be

$$m_{\rm top} = 173.7 \pm 0.8({\rm stat}+{\rm JES}) \pm 1.6({\rm syst})\ {\rm GeV}.$$

The systematic uncertainty is dominated by the uncertainty on the difference between the nominal inclusive response and the response of jets from b quarks in the calorimeter.

4. Top quark mass from production cross section

Two different schemes are commonly used to define the top quark mass: the $\overline{\rm MS}$ and the pole mass definition. Direct top quark mass measurements depend on leading-order Monte Carlo generators. It is not obvious how the top quark mass as implemented in LO MC generators exactly translates into a pole mass definition. In contrast, comparing the results from cross section measurements as a function of the top quark mass to fully inclusive calculations in higher order QCD with a well-defined mass definition allows an unambiguous extraction of the pole mass [8]. Using

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the combined measured cross sections from the lepton+jets, dilepton and lepton+tau channel and the NLO+NNLL calculations from S. Moch *et al.* [9] yields a top quark mass of

$$m_{\rm top} = 169.1^{+5.9}_{-5.2}({\rm stat}+{\rm syst})\ {\rm GeV}.$$

This result is in good agreement with the direct measurements.

5. Top-antitop quark mass difference

In the Standard Model, particles and antiparticles are assumed to have same mass. Any observed deviation would indicate CPT violation. Replacing the top quark mass and the JES parameter in the lepton+jets Matrix Element analysis with a free parameter for the top and antitop quark mass, the difference between both can be evaluated. A first measurement of the mass difference between a bare quark and antiquark was performed in the lepton+jets channel using 1 fb^{-1} of data [10]. With a difference of

$$m_{\rm top} - m_{\bar{\rm top}} = 3.8 \pm 3.7({\rm stat}+{\rm syst})\ {\rm GeV}$$

the measurement is consistent with the Standard Model expectation. As this result is still dominated by the statistical uncertainty, future measurements using larger data sets will improve the accuracy.

6. Top quark width

While the top quark mass is very precisely known, the top quark width is not. A template-based measurement has been performed at the CDF experiment but only sets an upper limit of 7.6 GeV at 95% C.L. [11]. Comparing this result to the next-to-leading order Standard Model expectation of 1.3 GeV at a top quark mass of 170 GeV, the experimental precision is quite poor. This is due the fact, that the detector resolution of the final state particles is usually larger than the top quark width. To achieve a more precise estimation, the DØ experiment assumes that the coupling in the t-channel single top quark production and the top quark decay are identical, i.e. $\sigma(t-{\rm channel}) \propto \Gamma(W \to tb)$. Combining the measurement of the branching fraction $BR(t \to Wb) = 0.96^{+0.09}_{-0.08}({\rm stat}+{\rm syst})$ [12] and the single top production cross section $\sigma(t-{\rm channel}) = 3.14^{+0.94}_{-0.84}({\rm stat}+{\rm syst}){\rm pb}$ [13], the total width of the top quark can be extracted via

$$\Gamma_{top} = \frac{\sigma(t-{\rm channel})\Gamma(W \to tb)_{\rm SM}}{BR(t \to Wb)\sigma(t-{\rm channel})_{\rm SM}}. \tag{6.1}$$

Using a statistical Bayesian approach, the top quark width has been measured to be

$$\Gamma_{top} = 2.05^{+0.57}_{-0.52}({\rm stat}+{\rm syst})\ {\rm GeV},$$

in agreement with the Standard Model prediction. This can be transformed into a lifetime of the top quark of $\tau_{top} = 3.2^{+1.1}_{-0.7}({\rm stat}+{\rm syst})10^{-25}s$. The measurement also offers a window to study new physics. For example, it can be used to set an upper limit on a 4^{th} generation b' quark of $|V_{tb'}| < 0.63$ at 95% C.L. assuming unitarity of the 4×4 CKM matrix, $m_{b'} > m_{top} - m_W$ and a flat prior for $|V_{tb}|$ between 0 and 1. [14].

7. Conclusion

The top quark mass has been measured at the DØ experiment in different final states using multiple techniques. In the dilepton channel, the largest systematic uncertainty arises from the jet energy scale. This has been addressed in the lepton+jets channel with a simultaneous measurement of the top quark mass and the jet energy scale which is well constrained by the mass of the hadronically decaying W boson. Combining all measurements with the Best Linear Unbiased Estimate, the top quark mass is determined at the DØ experiment to be m_{top} = 174.2 $\pm$ 1.7 (stat+syst) GeV [15]. The top quark mass has also been extracted from cross section measurements by comparing them to fully inclusive calculations in higher-order QCD. Both measurements, direct and indirect, are in good agreement as shown in Fig. 1. For the first time, the difference of the top and antitop quark mass has been evaluated at the DØ experiment. With $m_{\text{top}} - m_{\bar{\text{top}}}$ = 3.8 $\pm$ 3.7 (stat+syst) GeV, no deviation within uncertainties has been observed. Assuming that the coupling in t-channel single top quark production and top quark decay are identical, the top quark width has been determined with a precision of about 25%. The measured value of 2.1$\pm$ 0.6 GeV is in good agreement with the next-to-leading order expectation of 1.3 GeV for an assumed top quark mass of 170 GeV.

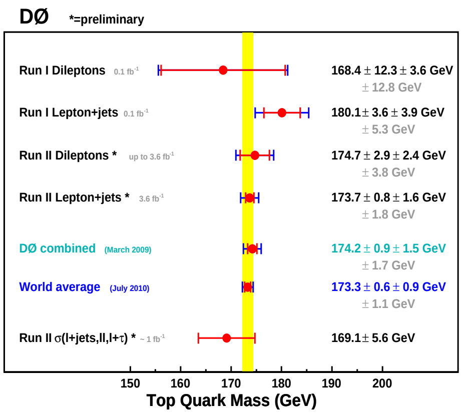

Figure 1: Combination of the Run I and Run II measurements of the top quark mass at the DØ experiment in the lepton+jets and dilepton decay channel, as well as the current world average.

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